

# Forward particle productions at RHIC and the LHC from CGC within local rcBK evolution

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**Abstract.** In order to describe forward hadron productions in high-energy nuclear collisions, we propose a Monte-Carlo implementation of Dumitru-Hayashigaki-Jalilian-Marian formula with the unintegrated gluon distribution obtained numerically from the running-coupling BK equation. We discuss influence of initial conditions for the BK equation by comparing a model constrained by global fit of small- $x$  HERA data and a newly proposed one from the “running coupling MV model.”

## 1. Phenomenology with rcBK equation

Relativistic Heavy-Ion Collider (RHIC) at Brookhaven, the QGP machine, has provided a new opportunity to explore the physics of the dense gluonic state at small Bjorken’s  $x$  in incoming hadrons, which is called Color Glass Condensate (CGC) [1]. Analyses of (e.g.) deeply inelastic scatterings (DIS) at HERA[2, 3] and heavy-ion collisions at RHIC[4] support the phenomenology based on the CGC picture.

A recent highlight is the inclusion of the running coupling effects in the Balitsky-Kovchegov equation (the rcBK equation) [5, 6], which controls the  $x$ -evolution of the unintegrated gluon distribution  $\tilde{\mathcal{N}}(k, y)$  in the incoming hadron ( $k$  is the transverse momentum and  $y = \ln(1/x)$  is the rapidity), which is obtained as the Fourier-transform of the ‘dipole scattering amplitude’  $\mathcal{N}(r, y)$  with  $r$  being the transverse size of a dipole. The rcBK equation has been confronted with the global analysis of DIS[7] as well as with the data obtained in proton-proton (pp), proton-nucleus (pA) and nucleus-nucleus (AA) collisions [8, 9, 10, 11] (see [12] for recent progress). Our goal is to elaborate a detailed model for particle productions in forward regions at RHIC and the Large Hadron Collider (LHC), by applying the gluon distribution obtained from the rcBK equation.

## 2. Forward particle production

### 2.1. Initial conditions for rcBK equation

With the DIS data for  $x < x_0$  accumulated at HERA, one can constrain the numerical solution of the rcBK equation quite accurately. This program was accomplished in [7]

by choosing an initial condition at  $x = x_0 = 0.01$  as (e.g.)

$$\mathcal{N}(r, y_0) = 1 - \exp \left[ -\frac{(r^2 Q_{s0}^2)^\gamma}{4} \ln \left( \frac{1}{\Lambda r} + e \right) \right] . \quad (1)$$

Among several parameter sets now available, we adopt here the AAMQS parameter set  $h$  ( $Q_{s0}^2 = 0.1597 \text{ GeV}^2$ ,  $\gamma = 1.118$ ,  $C = 2.47$ ,  $\Lambda = 0.241 \text{ GeV}$ ,  $\alpha_{\text{fr}}=1$ ) [7].

In addition, we will try a new initial condition, motivated by the McLerran-Venugopalan model with the running coupling modification (rcMV) [13]:

$$\mathcal{N}(r, y_0) = \frac{\alpha_\mu}{\alpha_s(r)} \left[ 1 - \exp \left( -\frac{r^2 Q_A^2}{4} \right) \right] , \quad (2)$$

where  $\alpha_s(r) = 1/[b_0 \ln(4C^2/(r^2\Lambda^2) + e)]$  with  $b_0 = (11 - 2N_f/3)/4\pi$  with  $N_f = 3$ , and  $\alpha_\mu$  is fixed by requiring that maximum value of  $\mathcal{N}(r, y_0)$  be unity. We have set  $\mathcal{N}(r, y_0) = 1$  for  $r$  larger than this maximum point. For the rcMV initial condition we use the parameters  $C = 1$ ,  $\Lambda = 0.2 \text{ GeV}$ ,  $Q_A^2 \equiv Q_{s0}^2 / \ln(Q_{s0}^2/\Lambda^2)$  with  $Q_{s0}^2 = 0.2 \text{ GeV}^2$  as a trial.

## 2.2. DHJ formula

In particle productions at very forward rapidities  $y > 0$  one can probe the saturation regime of one of the colliding hadrons. In this situation a factorized formula for the cross section is proposed by Dumitru, Hayashigaki, and Jalilian-Marian (DHJ)[14]:

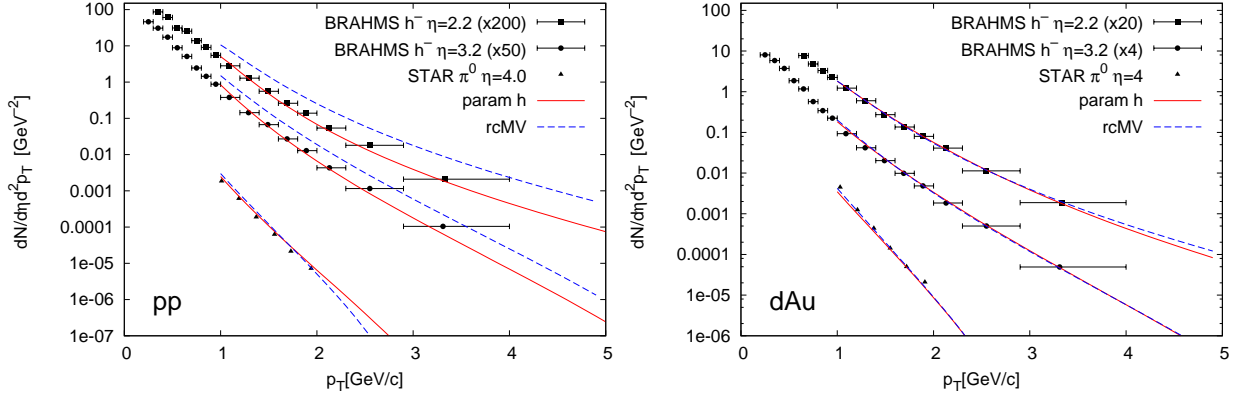
$$\frac{dN}{dy_h d^2p_T} = \frac{K}{(2\pi)^2} \sum_i \int_{x_F}^1 \frac{dz}{z^2} x_1 f_{i/p}(x_1, p_T^2) \tilde{\mathcal{N}} \left( \frac{p_T}{z}, x_2 \right) D_{h/i}(z, p_T^2) , \quad (3)$$

where  $f_{i/p}$  is the collinear distribution function for the large- $x_1$  parton  $i$ ,  $\tilde{\mathcal{N}}$  describes the small- $x_2$  unintegrated gluon distribution, and  $D_{h/i}$  deals with the high- $p_T$  fragmentation of a parton  $i$  into a hadron  $h$  with the momentum fraction  $z$ . The parameter  $K$  is introduced to absorb the higher-order contributions. In AA collisions,  $f_{i/p}$  and  $\tilde{\mathcal{N}}$  are to be generalized to those for nuclei.

The formula (3) was applied [14] to forward hadron productions in d-Au collisions at RHIC, with adopting a certain CGC model for  $\tilde{\mathcal{N}}$ . The larger gluon density in a nucleus is advantageous for probing the saturation effects. Recently Albacete and Marquet[9] exploited the rcBK equation to improve the  $\tilde{\mathcal{N}}$  part theoretically. Assuming a homogeneous nucleus in the transverse plane, they obtained the best description to date for the rapidity and momentum dependence of the d-Au data at RHIC.

## 2.3. Monte-Carlo implementation for nuclear collisions: the MC-DHJ/rcBK model

For more quantitative study, we need a nuclear model including the impact-parameter dependence and initial fluctuations. In a MC implementation developed in [15], nucleons are randomly sampled according to the Woods-Saxon density in an event-by-event basis, and the initial saturation momentum  $Q_{s0}^2$  in (1) and (2) is taken to be  $Q_{s0}^2 = N(\mathbf{r}_\perp) Q_{sp}^2$  at each transverse coordinate, where  $N(\mathbf{r}_\perp)$  is the number of nucleons in the dense target within a transverse area  $S_\perp$ . We apply locally in the transverse plane the numerical



**Figure 1.** Comparison of forward hadron spectra computed with the AAMQS set  $h$  (solid) and rcMV (dashed) to the data observed at RHIC. The  $K$  factor is chosen as  $K = 1.5$  for charged particles ( $h^-$ ) and  $K = 0.5$  for  $\pi^0$  in pp and d-Au collisions.

solutions for the rcBK equation with different initial values of  $Q_{s0}^2$ . Such an approach has been pursued within the so-called  $k_\perp$  factorization approximation for AA collisions, which reproduces successfully the centrality dependence of the hadron multiplicity at RHIC and the LHC[15, 10, 11].

Here we combine the DHJ formula with the rcBK evolution in the MC implementation (MC-DHJ/rcBK). That is, we compute particle productions *at each transverse grid*  $\mathbf{r}_\perp$  using the DHJ formula (3) with  $\tilde{N}(k, y)$  numerically obtained from  $Q_{s0}^2$  at grid  $\mathbf{r}_\perp$  determined by the MC code:

$$\frac{dN}{dy_h d^2 p_T d\mathbf{r}_\perp} = T_d(\mathbf{r}_\perp) \times \left. \frac{dN}{dy_h d^2 p_T} \right|_{\text{DHJ } \mathbf{r}_\perp}. \quad (4)$$

Here  $T_d(\mathbf{r}_\perp)$  is the thickness function on the dilute side. We stress as an advantage of this approach that *there is no more additional parameter* after fitting pp collisions. We comment also that the MC implementation allows us to study the initial fluctuations[15].

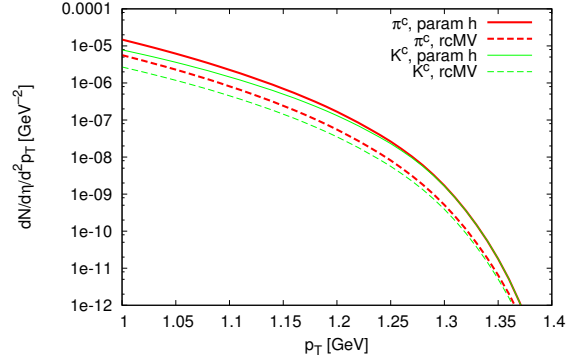
### 3. Results

We use for  $f_{i/p}$  and  $D_{h/i}$  the CTEQ6M NLO PDF [16] and DSS NLO fragmentation functions [17], respectively, and set the factorization scale to  $\mu^2 = p_T^2$ . We remark that an oscillation appears in  $\tilde{N}(k, y)$  for smaller  $Q_{s0}^2$  when a sharp cutoff for the running coupling  $\alpha_s(r) = 1/[b_0 \ln(4C^2/r^2\Lambda^2)]$  is adopted at  $\alpha_{fr}$ . Thus we tried a smooth cutoff  $\alpha_s(r) = 1/[b_0 \ln(4C^2/r^2\Lambda^2) + a]$  where constant  $a$  is adjusted to make  $\alpha_s(r) \rightarrow 2$  as  $r \rightarrow \infty$  in the rcBK evolution in the case of the rcMV initial condition.

In figure 1, transverse momentum distributions of negatively charged hadrons  $h^-$  at pseudo-rapidities  $\eta = 2.2$  and  $3.2$  from BRAHMS [18] and neutral pions  $\pi^0$  at  $\eta = 4$  from STAR [19] in pp and d-Au collisions at  $\sqrt{s} = 200$  GeV are compared to our results. The AAMQS set  $h$  with  $K = 1.5$  ( $0.5$ ) describes the forward particle multiplicities of  $h^-$  ( $\pi^0$ ) very nicely in pp and d-Au collisions

at the same time without changing any parameters in the model. On the other hand, the rcMV initial condition with our current parameter set with  $K = 1.5$  (0.5) for  $h^-$  ( $\pi^0$ ) leads to a good agreement with the data for d-Au collisions, but not for pp collisions. It is very interesting to do global analysis of HERA data by using rcMV initial condition and fix the parameters. We will report more systematic analyses on the parameter dependence elsewhere.

Finally a result from test calculations of the MC-DHJ/rcBK at extremely forward rapidity  $\eta = 8.5$  for pp collisions at  $\sqrt{s} = 7$  TeV, which is measured in LHCf experiment [20], is shown in figure 2. One expects that dependence of the rcBK evolution on initial conditions will become weaker at higher energies, but we see that the result is still relatively sensitive to the initial conditions.



**Figure 2.** Transverse momentum spectra of average of charged pions (bold) and of charged kaons (thin) at  $\eta = 8.5$  for pp collisions at  $\sqrt{s} = 7$  TeV from MC-DHJ/rcBK model ( $K=1$ ) with the AAMQS set  $h$  (solid) and rcMV (dashed).

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